

# Pair production of the heavy leptons in future high energy linear $e^+e^-$ colliders

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## Abstract

The littlest Higgs model with T-parity predicts the existence of the T-odd particles, which can only be produced in pair. We consider pair production of the T-odd leptons in future high energy linear  $e^+e^-$  collider (*ILC*). Our numerical results show that, as long as the T-odd leptons are not too heavy, they can be copiously produced and their possible signals might be detected via the processes  $e^+e^- \rightarrow \bar{L}_i L_j$  in future *ILC* experiments.

## 1. Introduction

Many popular specific models beyond the standard model ( $SM$ ) predict the existence of the heavy leptons. It is well known that, so far, a clear signal of such new fermions has not been found at high energy collider experiments. However, the experimental lower bounds for the heavy lepton mass was found to be  $44GeV$  by  $OPAL$ [1],  $46GeV$  by  $HLEPH$ [2], and  $90GeV$  by  $H1$  Collaborations[3]. This means that, if this kind of new particles indeed exist, they should be detected in future high energy collider experiments. Any signal for such kind of fermions in future high energy experiments will play an important role in discovery of the new physics beyond the  $SM$ .

Little Higgs theory[4] is proposed as an interesting solution to so called hierarchy problem of the  $SM$  and can be regarded as one of the important candidates of the new physics beyond the  $SM$ . Among of the little Higgs models, the Littlest Higgs ( $LH$ ) model[5] is one of the simplest and phenomenologically viable models, which has all essential features of the little Higgs models. However, the  $LH$  model suffers from severe constraints from precision electroweak measurement, which could only be satisfied by fine tuning the model parameters[6]. To avoid this serious problem, a new discrete symmetry (called T-parity) has been introduced, which forms called  $LHT$  model[7]. In this model, all dangerous tree level contributions to low energy electroweak observables are forbidden by T-parity and hence the corrections to observables are loop suppressed. The  $LHT$  model is one of the attractive little Higgs models.

In order to implement T-parity in fermion sector, one introduces three doublets of “mirror quarks” and three doublets of “mirror leptons”, which have T-odd parity, transform vectorially under  $SU(2)_L$  and can be given a large mass. A first study of the collider phenomenology of the  $LHT$  model was given in Ref.[8]. The possible signals of the T-odd fermions (mirror fermions) have been studied in Refs.[9,10,11,12]. In this paper, we will focus our attention on the T-odd leptons and see whether the possible signals of the  $LHT$  model can be detected in future high energy linear  $e^+e^-$  collider ( $ILC$ ) experiments via the production which are related the T-odd leptons.

Studying production and decay of the new charged leptons at high energy collider

experiments is of special interest. It will be helpful to test the  $SM$  flavor structure and new physics beyond the  $SM$ . This fact has lead to many studies involving the new charged leptons at  $e^+e^-$  colliders[13],  $ep$  colliders[14], and hadron colliders[15]. Although there are lot of works on the new charged leptons in the literature, it is need to be further studied in the context of the  $LHT$  model. There are several motivations to perform this study. First, the  $LHT$  model is one of the attractive little Higgs models, which predicts the existence of the T-odd heavy charged leptons. However, in previous works on studying the phenomenology of the  $LHT$  model, studies about the heavy charged leptons are very little. Second, a pair of the T-odd leptons can be directly produced at the  $CERN$  Large Hadron Collider ( $LHC$ ) through s-channel exchange of the  $SM$  gauge bosons. However, its production cross section is very small in most of the parameter space of the  $LHT$  model[9,12]. So far, a complete study on pair production of the T-odd charged leptons has not been presented in the context of the  $LHT$  model. Third, studying the possible signals of the heavy charged leptons in future high energy colliders can help the collider experiments to test little Higgs models and distinguish different new physics models. Thus, in this paper, we will concentrate our attention on pair production of the heavy charged leptons (T-odd) in future  $ILC$  experiments.

In the present work, we study the dynamical properties for production of the T-odd leptons and also for decay of the T-odd leptons into presently known particles. We also discuss how the signals can be clearly separated from the  $SM$  backgrounds with a great significance. After reviewing the  $LHT$  model in section 2, the production processes and signatures of the T-odd leptons are studied in detail in section 3. Finally, our conclusions and simple discussions are given in section 4.

## 2. The $LHT$ model

In this section, we briefly review the essential features of the  $LHT$  model studied in Ref.[7], which are related our calculation. Similar with the  $LH$  model, the  $LHT$  model is based on an  $SU(5)/SO(5)$  global symmetry breaking pattern. A subgroup  $[SU(2) \times U(1)]_1 \times [SU(2) \times U(1)]_2$  of the  $SU(5)$  global symmetry is gauged, and at the scale  $f$  it is broken into the  $SM$  electroweak symmetry  $SU(2)_L \times U(1)_Y$ . T-parity

is an automorphism which exchanges the  $[SU(2) \times U(1)]_1$  and  $[SU(2) \times U(1)]_2$  gauge symmetries. The T-even combinations of the gauge fields are the  $SM$  electroweak gauge bosons  $W_\mu^a$  and  $B_\mu$ . The T-odd combinations are T-parity partners of the  $SM$  electroweak gauge bosons.

After taking into account electroweak symmetry breaking ( $EW\!SB$ ), at the order of  $\nu^2/f^2$ , the masses of the T-odd set of the  $SU(2) \times U(1)$  gauge bosons are given as:

$$M_{B_H} = \frac{g'f}{\sqrt{5}}[1 - \frac{5\nu^2}{8f^2}], \quad M_{Z_H} \approx M_{W_H} = gf[1 - \frac{\nu^2}{8f^2}]. \quad (1)$$

Where  $\nu = 246 GeV$  is the electroweak scale and  $f$  is the scale parameter of the gauge symmetry breaking of the  $LHT$  model.  $g'$  and  $g$  are the  $SM$   $U(1)_Y$  and  $SU(2)_L$  gauge coupling constants, respectively. Because of the smallness of  $g'$ , the T-odd gauge boson  $B_H$  is the lightest T-odd particle, which can be seen as an attractive dark matter candidate[16].

To avoid severe constraints and simultaneously implement T-parity, it is need to double the  $SM$  fermion doublet spectrum[7,8,17]. The T-even combination is associated with the  $SU(2)_L$  doublet, while the T-odd combination is its T-parity partner. The masses of the T-odd fermions can be written in a unified manner as:

$$M_{F_i} = \sqrt{2}k_i f, \quad (2)$$

where  $k_i$  are the eigenvalues of the mass matrix  $k$  and their values are generally dependent on the fermion species  $i$ .

The mirror fermions (T-odd quarks and T-odd leptons) have new flavor violating interactions with the  $SM$  fermions mediated by the new gauge bosons ( $B_H, W_H^\pm$ , or  $Z_H$ ), which are parameterized by four  $CKM$ -like unitary mixing matrices, two for mirror quarks and two for mirror leptons[11,12,18]:

$$V_{Hu}, \quad V_{Hd}, \quad V_{Hl}, \quad V_{H\nu}. \quad (3)$$

They satisfy:

$$V_{Hu}^+ V_{Hd} = V_{CKM}, \quad V_{H\nu}^+ V_{Hl} = V_{PMNS}. \quad (4)$$

Where the  $CKM$  matrix  $V_{CKM}$  is defined through flavor mixing in the down-type quark sector, while the  $PMNS$  matrix  $V_{PMNS}$  is defined through neutrino mixing. Similar with Ref.[11], we will set the Majorana phases of  $V_{PMNS}$  to zero in our following calculation. The matrix  $V_{Hl}$  can give rise to the lepton flavor violating processes.

The couplings of the T-odd leptons to other particles, which are related our analysis, are summarized as[11]:

$$Z\bar{L}_i L_j : \frac{ie}{S_w C_w} [-\frac{1}{2} + S_w^2] \gamma^\mu \delta_{ij}, \quad \gamma \bar{L}_i L_j : -ie \gamma^\mu \delta_{ij}; \quad (5)$$

$$Z_H \bar{L}_i l_j : \frac{ie}{S_w} [-\frac{1}{2} + \frac{S_w^2}{8(5C_w^2 - S_w^2)} \frac{\nu^2}{f^2}] (V_{Hl})_{ij} \gamma^\mu P_L; \quad (6)$$

$$B_H \bar{L}_i l_j : \frac{ie}{C_w} [\frac{1}{10} + \frac{5C_w^2}{8(5C_w - S_w^2)} \frac{\nu^2}{f^2}] (V_{Hl})_{ij} \gamma^\mu P_L. \quad (7)$$

Where  $S_w = \sin \theta_w$ ,  $\theta_w$  is the Weinberg angle.  $l_i$  and  $L_j$  represent the three family leptons  $e, \mu$ , or  $\tau$  and their T-odd partners, respectively.  $P_L = (1 - \gamma_5)/2$  is the left-handed projection operator.

From above discussions, we can see that the  $LHT$  model provides a new mechanism for lepton flavor violation ( $LFV$ ), which comes from the flavor mixing in the mirror lepton sector. Thus, the  $LHT$  model can give significantly contributions to some  $LFV$  processes, such as  $l_i \rightarrow l_j \gamma$ ,  $l_i \rightarrow l_j l_k l_l$ ,  $\tau \rightarrow \mu \pi$  etc[19]. In the next section, we will consider pair production of the T-odd leptons in future  $ILC$  experiments and further discuss their  $LFV$  signatures.

### 3. Pair production of the T-odd leptons at the $ILC$

In the  $LHT$  model[7], T-parity explicitly forbids the tree level contributions coming from the new particles to the observables involving only the  $SM$  particles and forbids the interactions that induce triplet vacuum expectation value ( $VEV$ ) contributions. The  $SM$  particles are T-even, while the new particles are T-odd, except for the T-parity partner of the top quark. As a consequence, the electroweak precision measurement data allow for a relatively low value of the new particle mass scale  $f \sim 500 GeV$  and the T-odd particles can only be produced in pairs. Pair production of the T-odd particles has been studied

via  $pp$ [9,12],  $e\gamma$  and  $ep$  collisions[20].

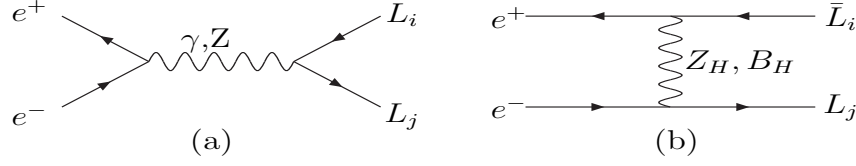


Figure 1: Feynman diagrams for pair production of the T-odd leptons at the  $ILC$ .

From above discussions, we can see that pair production of the T-odd leptons at  $ILC$  proceeds via the s-channel and t-channel Feynman diagrams as shown in Fig.1. The invariant scattering amplitude for the process  $e^+(P_1)e^-(P_2) \rightarrow \bar{L}_i(P_3)L_j(P_4)$  can be written as:

$$\begin{aligned}
iM = & \frac{e^2}{K_1^2} \bar{v}(P_1) \gamma^\mu u(P_2) \bar{u}(P_4) \gamma_\mu v(P_3) \\
& + \frac{e^2}{4S_w^2 C_w^2} \frac{1}{K_1^2 - M_Z^2} \left[ -\frac{1}{2} + S_w^2 \right] \bar{v}(P_1) (4S_w^2 - 1 + \gamma_5) \gamma^\mu u(P_2) \bar{u}(P_4) \gamma_\mu v(P_3) \\
& + \frac{a^2 (V_{Hl})_{ei} (V_{Hl})_{ej}}{K_2^2 - M_{Z_H}^2} \bar{v}(P_1) \gamma^\mu P_L v(P_3) \bar{u}(P_4) \gamma_\mu P_L u(P_2) \\
& + \frac{b^2 (V_{Hl})_{ei} (V_{Hl})_{ej}}{K_2^2 - M_{Z_H}^2} \bar{v}(P_1) \gamma^\mu P_L v(P_3) \bar{u}(P_4) \gamma_\mu P_L u(P_2),
\end{aligned} \tag{8}$$

where

$$K_1^2 = (P_1 + P_2)^2, \quad K_2^2 = (P_4 - P_2)^2; \tag{9}$$

$$a = \frac{e}{S_w} \left[ -\frac{1}{2} + \frac{S_w^2}{8(5C_w^2 - S_w^2)} \frac{v^2}{f^2} \right], \quad b = \frac{e}{C_w} \left[ -\frac{1}{10} + \frac{5C_w^2}{8(5C_w^2 - S_w^2)} \frac{v^2}{f^2} \right]. \tag{10}$$

From Eqs.(8), (9), and (10) we can see that, except the  $SM$  input parameters  $\alpha_e = 1/128.8$ ,  $S_w^2 = 0.2315$ , and  $M_Z = 91.187 GeV$ [21], the production cross sections  $\sigma(\bar{L}_i L_j)$  for the processes  $e^+e^- \rightarrow \bar{L}_i L_j$  are dependent on the model dependent parameters  $f, k$  (or  $M_{L_i}$ ),  $(V_{Hl})_{ei}$ , and  $(V_{Hl})_{ej}$ . The matrix elements  $(V_{Hl})_{ij}$  can be determined through  $V_{Hl} = V_{H\nu} V_{PMNS}$ . To avoid any additional parameters introduced and to simplify our calculation,

we take  $V_{Hl} = V_{PMNS}$ , which means that the T-odd leptons have no impact on flavor violating observables in the neutrino sector. For the matrix  $V_{PMNS}$ , we take the standard parameterization form with parameters given by the neutrino experiments[22,23]. Ref.[19] has shown that, for  $V_{Hl} = V_{PMNS}$ , to make the  $\mu \rightarrow e\gamma$  and  $\mu^- \rightarrow e^-e^+e^-$  decay rates consistent with the present experimental upper bounds, the spectrum of the T-odd leptons must be quasi-degenerate. Thus, in our numerical estimation, we will assume  $M_{L_e} = M_{L_\mu} = M_{L_\tau} = M_L$  and take the parameters  $f$  and  $M_L$  as free parameters.

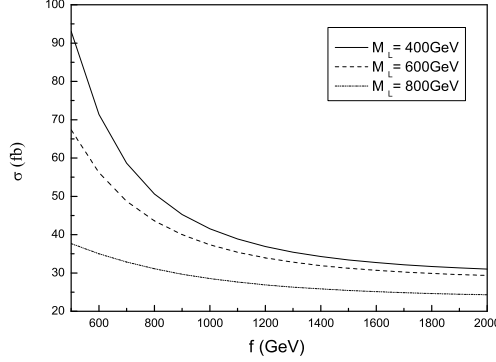


Figure 2: The production cross section  $\sigma(\bar{L}_\mu L_\mu)$  as a function of the scale parameter  $f$  for  $\sqrt{s} = 2\text{TeV}$  and three values of the T-odd lepton mass  $M_L$ .

Our numerical results are shown in Fig.2 and Fig.3, in which we plot the production cross sections  $\sigma(\bar{L}_\mu L_\mu)$  and  $\sigma(\bar{L}_e L_\mu)$  as functions of the scale parameter  $f$  for the center-of-mass  $\sqrt{s} = 2\text{TeV}$  and three values of the T-odd lepton mass  $M_L$ . Since the value of the matrix element  $(V_{PMNS})_{e\tau}$  is smaller than that of  $(V_{PMNS})_{e\mu}$ , the production cross sections  $\sigma(\bar{L}_\tau L_\tau)$  and  $\sigma(\bar{L}_e L_\tau)$ [or  $\sigma(\bar{L}_\mu L_\tau)$ ] are smaller than  $\sigma(\bar{L}_\mu L_\mu)$  and  $\sigma(\bar{L}_e L_\mu)$ , respectively. So, in Fig.2 and Fig.3, we have not given the curves for the production cross sections  $\sigma(\bar{L}_\tau L_\tau)$ ,  $\sigma(\bar{L}_e L_\tau)$ , and  $\sigma(\bar{L}_\mu L_\tau)$ . Using the unitarity based *PDG* parametrization and available data from oscillation experiments, Refs.[22,23] have constructed the *PMNS* matrix  $V_{PMNS}$ , in which the values of the matrix elements  $(V_{PMNS})_{e\mu}$  and  $(V_{PMNS})_{ee}$  are given in the ranges of  $0.4871 \sim 0.6193$  and  $0.7575 \sim 0.8819$ , respectively. To simply our calculation, we have taken the values of  $(V_{PMNS})_{e\mu}$  and  $(V_{PMNS})_{ee}$  as 0.55 and 0.82 in Fig.3 and Fig.2, respectively. From Fig.(2) and Fig.(3), we can see that the values

of the production cross sections increase as the scale parameter  $f$  decreasing and as the T-odd lepton mass  $M_L$  decreasing. For  $M_L = 400\text{GeV}$  and  $500\text{GeV} \leq f \leq 2000\text{GeV}$ , the values of  $\sigma(\bar{L}_\mu L_\mu)$  and  $\sigma(\bar{L}_e L_\mu)$  are in the ranges of  $93.1fb \sim 31fb$  and  $171.5fb \sim 33.5fb$ , respectively. While for  $M_L = 800\text{GeV}$  and  $500\text{GeV} \leq f \leq 2000\text{GeV}$ , their values are in the ranges of  $37.7fb \sim 24.3fb$  and  $55.2fb \sim 25.8fb$ , respectively. If we assume that the *ILC* experiment with  $\sqrt{s} = 2\text{TeV}$  has a yearly integrated luminosity of  $\mathcal{L} = 100fb^{-1}$  and assume  $M_L < 900\text{GeV}$  and  $f \leq 2\text{TeV}$ , then there will be several hundreds up to thousands of  $\bar{L}_\mu L_\mu$  or  $\bar{L}_e L_\mu$  events to be generated per year.

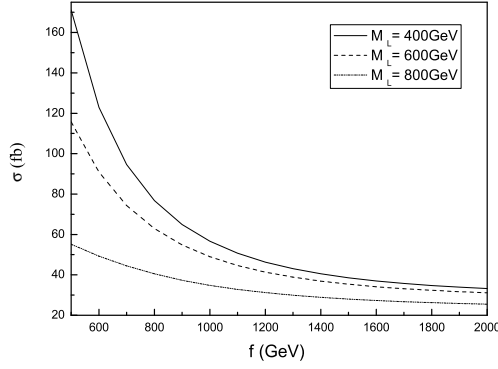


Figure 3: Same as Fig.2 but for the production cross section  $\sigma(\bar{L}_e L_\mu)$

The new gauge boson  $B_H$  is the lightest T-odd particle, which can be seen as an attractive dark matter candidate[16]. The T-odd lepton  $L_i$  mainly decays to  $B_H l_i (l_i = e, \mu \text{ or } \tau)$  and there is  $Br(L_i \rightarrow B_H l_i) \approx 100\%$ [9,12,23]. In this case, the signature of the process  $e^+e^- \rightarrow \bar{L}_\mu L_\mu$  is the opposite-sign same-flavor leptons  $\bar{\mu}\mu$  plus large missing energy i.e.  $\bar{\mu}\mu + B_H B_H$ . The large transverse missing energy can be used to distinguish the signal events from the *SM* signal events generated by the process  $e^+e^- \rightarrow \gamma/Z \rightarrow \bar{\mu}\mu$ , which can not be considered as background. The intrinsic *SM* backgrounds come from the processes  $e^+e^- \rightarrow \mu\bar{\mu}Z \rightarrow \mu\bar{\mu}\nu\bar{\nu}$  and  $e^+e^- \rightarrow W^+W^- \rightarrow \mu\bar{\mu}\nu_\mu\bar{\nu}_\mu$ . However, at the *ILC* experiment with  $\sqrt{s} = 2\text{TeV}$ , the cross section of the former process is about  $2fb$  while the one of the latter process is about  $11.2fb$ , which is smaller than the cross section of the process  $e^+e^- \rightarrow \bar{L}_\mu L_\mu$  in most of the parameter space of the *LHT* model. Thus, the signal event  $\bar{\mu}\mu + B_H B_H$  should be easily separated from the *SM* background with a



great significance. We expect that, as long as it is not too heavy, the T-odd lepton should be detected via the process  $e^+e^- \rightarrow \bar{L}_\mu L_\mu$  in future *ILC* experiments.

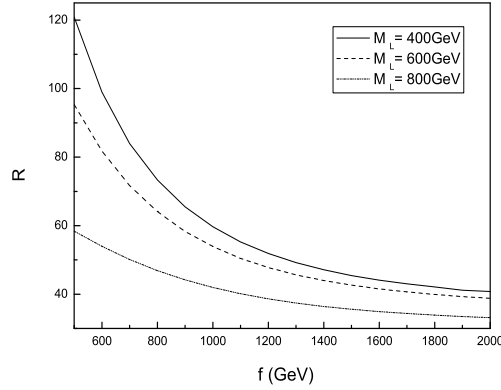


Figure 4: The statistical significance  $R = S/\sqrt{B}$  as a function of the scale parameter  $f$  for three values of the T-odd lepton mass  $M_L$ .

The *LFV* process  $e^+e^- \rightarrow \bar{L}_e L_\mu$  can give rise to the signal events with opposite-sign and different-flavor leptons and large missing energy ( $\bar{e}\mu + \cancel{E}_T$ ), i.e.  $e^+e^- \rightarrow \bar{L}_e L_\mu \rightarrow \bar{e}\mu B_H B_H$ . Although the *LFV* signal is quite spectacular, it is not free of the *SM* background. The leading *SM* backgrounds of the signal event  $\bar{e}\mu + \cancel{E}_T$  mainly come from the *WW* pair production process  $e^+e^- \rightarrow W^+W^- \rightarrow \bar{e}\mu\nu_e\bar{\nu}_\mu$ . To see whether the *LFV* signals of the T-odd leptons can be detected in future *ILC* experiments, we further calculate the ratio of the signal over the square root of the background  $R = S/\sqrt{B}$ , which is called statistical significance. Our numerical results are shown in Fig.4, in which we have taken the integrated luminosity  $\mathcal{L} = 100fb^{-1}$  for  $\sqrt{s} = 2TeV$  and the branching ratios  $Br(W^+ \rightarrow \bar{e}\nu_e) = (10.66 \pm 0.17)\%$  and  $Br(W^- \rightarrow \mu\bar{\nu}_\mu) = (10.60 \pm 0.15)\%$ [21]. From Fig.4 one can see that, in most of the parameter space of the *LHT* model, the value of the statistical significance  $R$  is larger than 33. Furthermore, if we apply appropriate cuts on the *SM* backgrounds, the value of the ratio  $R$  can be clearly improved. For example, Ref.[24] has shown that appropriate kinematical cuts can strongly reduce the *WW* background. Thus, the possible signals of the T-odd leptons should be easy detected via the *LFV* process  $e^+e^- \rightarrow \bar{L}_e L_\mu$  in future *ILC* experiments.

## 4. Conclusions and discussions

The *LHT* model is one of the attractive little Higgs models, which provides a possible dark matter candidate. To simultaneously implement T-parity, the *LHT* model introduces new mirror fermions (T-odd quarks and T-odd leptons). The flavor mixing in the mirror fermion sector gives rise to a new source of flavor violation, which might generate significantly contributions to some flavor violation processes.

The T-odd leptons can only be produced through weak processes and their production cross sections are generally small at the *LHC*. So, in this paper, we study pair production of the T-odd lepton in future *ILC* experiments. Our numerical results show that, as long as the T-odd leptons are not too heavy, they can be copiously produced in pairs. For example, for  $500\text{GeV} \leq f \leq 2000\text{GeV}$  and  $M_L = 600\text{GeV}$ , the production cross section for the process  $e^+e^- \rightarrow \bar{L}_\mu L_\mu$  is in the range of  $67.4\text{fb} \sim 29.3\text{fb}$ . Furthermore, the pair production process  $e^+e^- \rightarrow \bar{L}_\mu L_\mu$  can generate nice signal event  $\mu\bar{\mu} + \cancel{E}_T$ , which might be easily separated from the *SM* background with a great significance.

The T-odd leptons can also be produced in pair via the *LFV* processes  $e^+e^- \rightarrow \bar{L}_i L_j (i \neq j)$ . Except the free parameters  $f$  and  $M_L$ , their production cross sections are dependent on the *PMNS* matrix elements  $(V_{PMNS})_{ei}$  and  $(V_{PMNS})_{ej}$ . Considering the bounds of the neutrino oscillation experiment data on these matrix elements, we calculate the production cross section of the *LFV* process  $e^+e^- \rightarrow \bar{L}_e L_\mu$ . We find that its value can be significantly large in most of the parameter space of the *LHT* model. The *SM* backgrounds of this process mainly come from the *SM* process  $e^+e^- \rightarrow W^+W^-$ . Even if no cuts are applied and the electron beam and the positron beam are not polarized, the value of the ratio  $R$  can be larger than 33 in most of the parameter space.

In conclusion, we have considered pair production of the T-odd leptons and discussed the possible of detecting these new particles in future *ILC* experiments. We find that, as long as the T-odd leptons are not too heavy, they can be copiously produced in pairs via the processes  $e^+e^- \rightarrow \bar{L}_i L_j$  and their signatures might be observed in future *ILC* experiments. Thus, we expect that the future *ILC* experiments can be seen as an ideal tool to detect the T-odd leptons predicted by the *LHT* model. Even if we can not

observe the signals in future *ILC* experiments, at least, we can obtain the bounds on the free parameters of the *LHT* model.

The *LHT* model might give significantly contributions to some *LFV* processes, such as  $l_i \rightarrow l_j \gamma$ ,  $l_i \rightarrow l_j l_k l_l$ ,  $\tau \rightarrow \mu \pi$  etc. The present experimental upper bounds of branching ratios  $Br(\mu \rightarrow e \gamma)$  and  $Br(\mu^- \rightarrow e^- e^+ e^-)$  can give severe constraints on the free parameters of the *LHT* model[19]. Considering these constraints, we have assumed  $M_{L_e} = M_{L_\mu} = M_L$  for  $V_{Hl} = V_{PMNS}$  in our numerical estimation. From our numerical results, we can see that the values of the cross section  $\sigma(\bar{L}_e L_\mu)$  and  $\sigma(\bar{L}_\mu L_\mu)$  increase as the scale parameter  $f$  decreasing, which is similar with that for the branching ratios  $Br(\mu \rightarrow e \gamma)$  and  $Br(\mu^- \rightarrow e^- e^+ e^-)$ . However, even for  $M_L = 400 GeV$  and  $f \leq 2000 GeV$ , the values of  $\sigma(\bar{L}_\mu L_\mu)$  and  $\sigma(\bar{L}_e L_\mu)$  are larger than  $31 fb$  and  $33 fb$ , respectively. Thus, we can say that the strong constraints on the *LHT* model, which come from the *LFV* processes  $\mu \rightarrow e \gamma$  and  $\mu^- \rightarrow e^- e^+ e^-$ , do not strongly change our conclusions about production of the T-odd leptons in future *ILC* experiments.

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